



... for a brighter future



The Physics of the Blues

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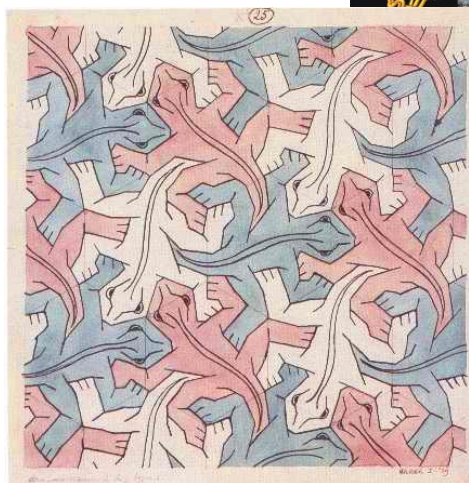
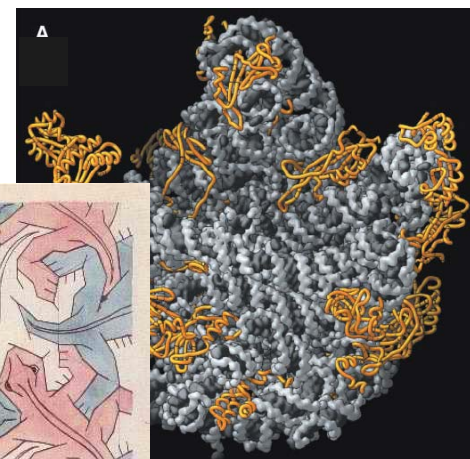


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Symbiosis of art and science

- Science and technology drives art



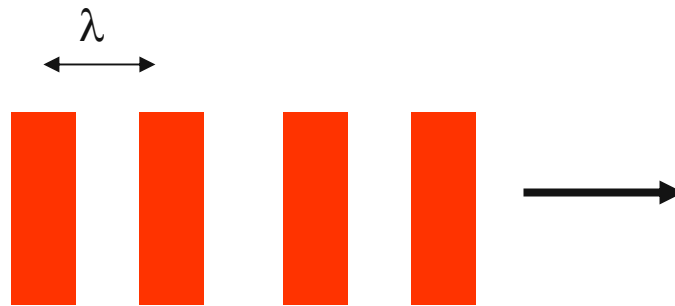
- Art drives science and technology

$$\nabla^2 \phi = 0$$



Musical Pitch

- The pitch of a note is determined only by the frequency of the sound (pressure) wave



high pressure is red

From a vibrating object, e.g. a string (guitar) or column of air (flute)
Frequency (f) depends inversely on the wavelength (λ) of the vibration (and other factors such as string. tension)

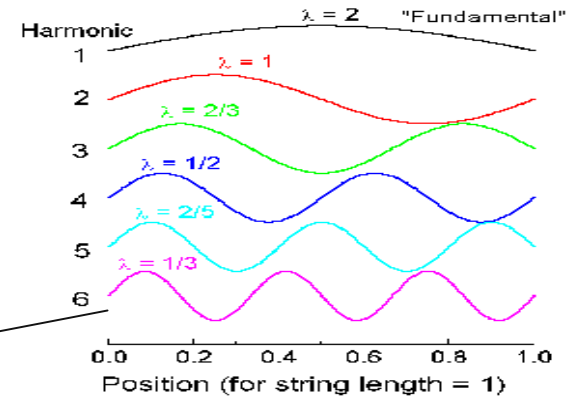
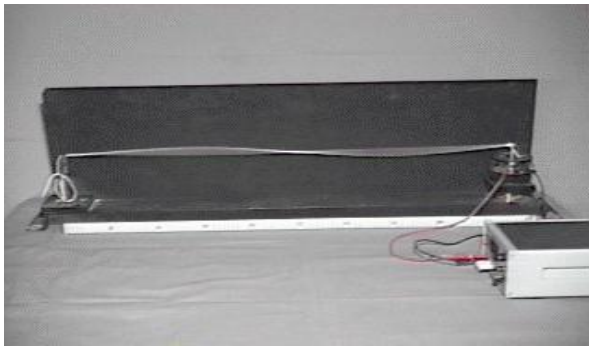


$$f = c / \lambda$$

Overtone of a string

For a vibrating string, all the harmonics (or overtones), are integer multiples of the fundamental frequency (pitch)

$$f_n = n f_0$$

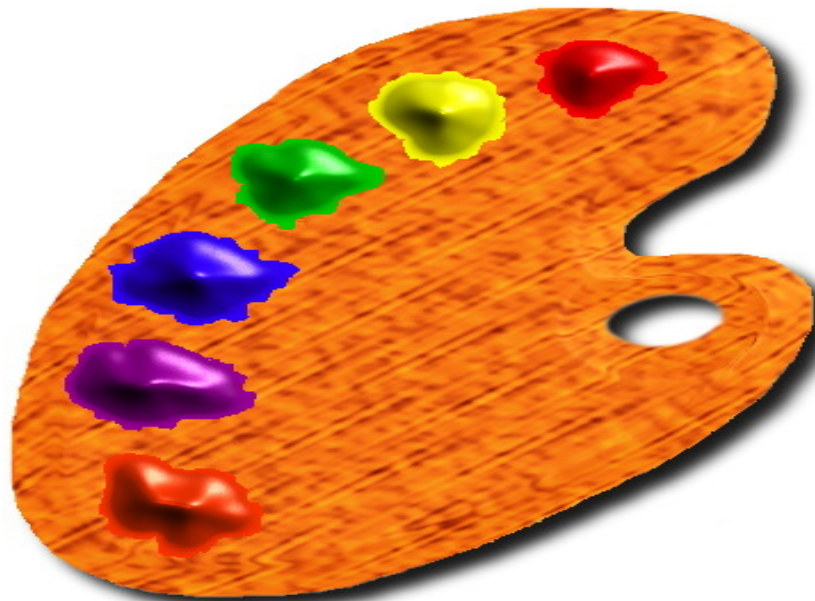


the shape of each harmonic is a “sine” wave

When you pluck the string you get a mixture of harmonics, but the amount of each depends on how you pluck it (timbre)

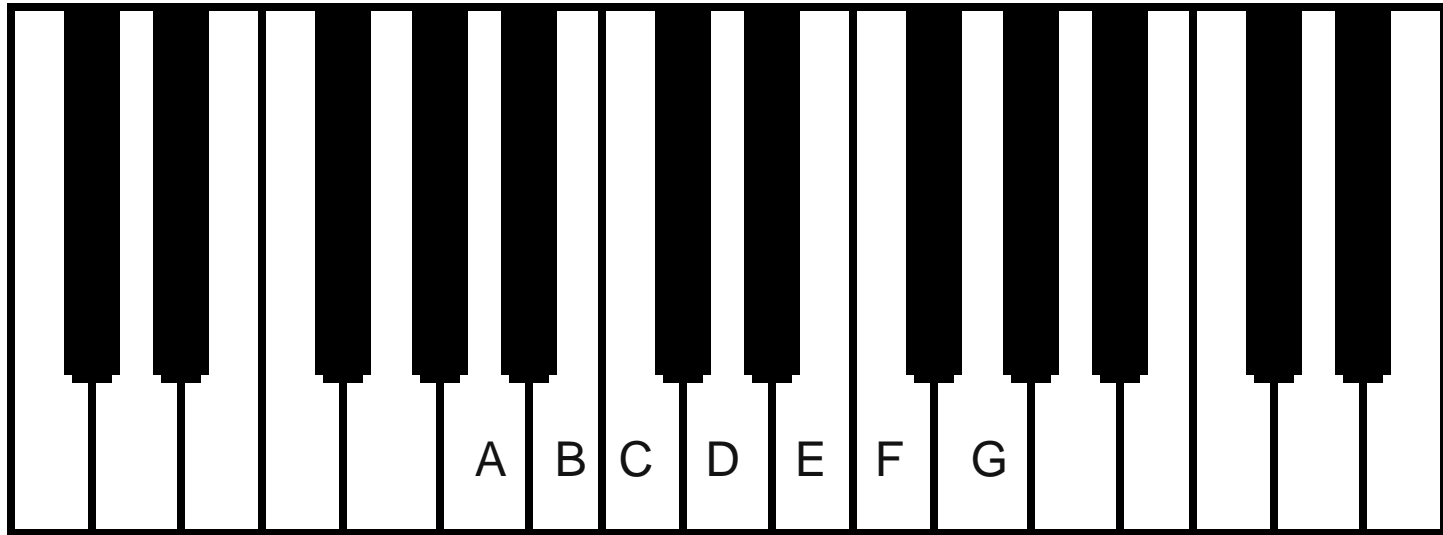
(harmonic or fourier analysis is the mathematical technique to extract the harmonics for the shape – very important in science and engineering)

Let's build a musical scale based on the harmonics...



the scale is to a musician as the palette is to an artist

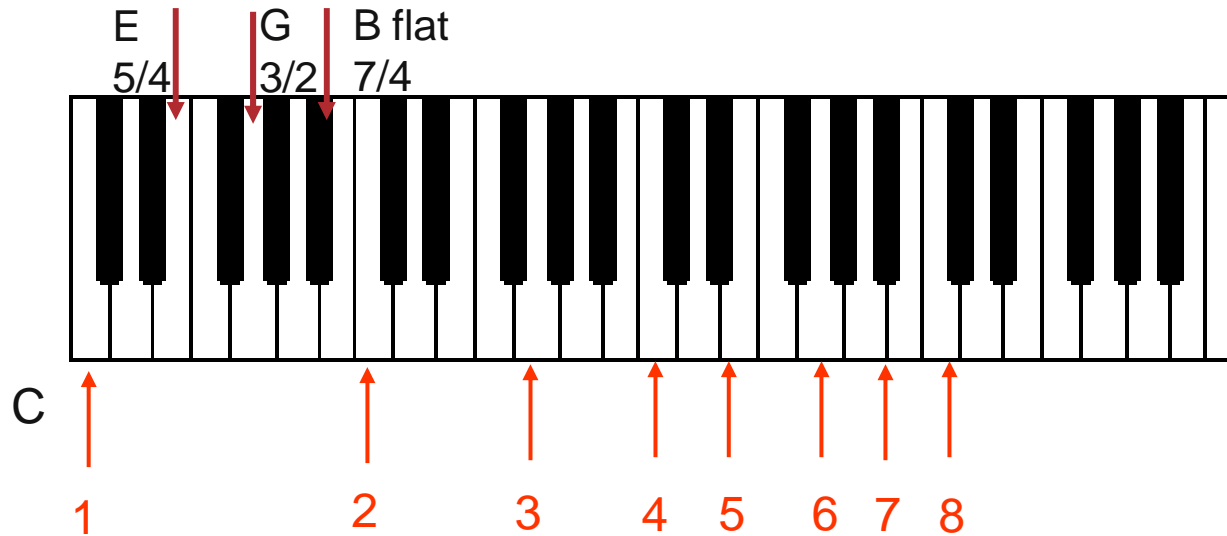
Familiarity with the keyboard



C D E F G A

1 step = semitone
2 steps = whole tone

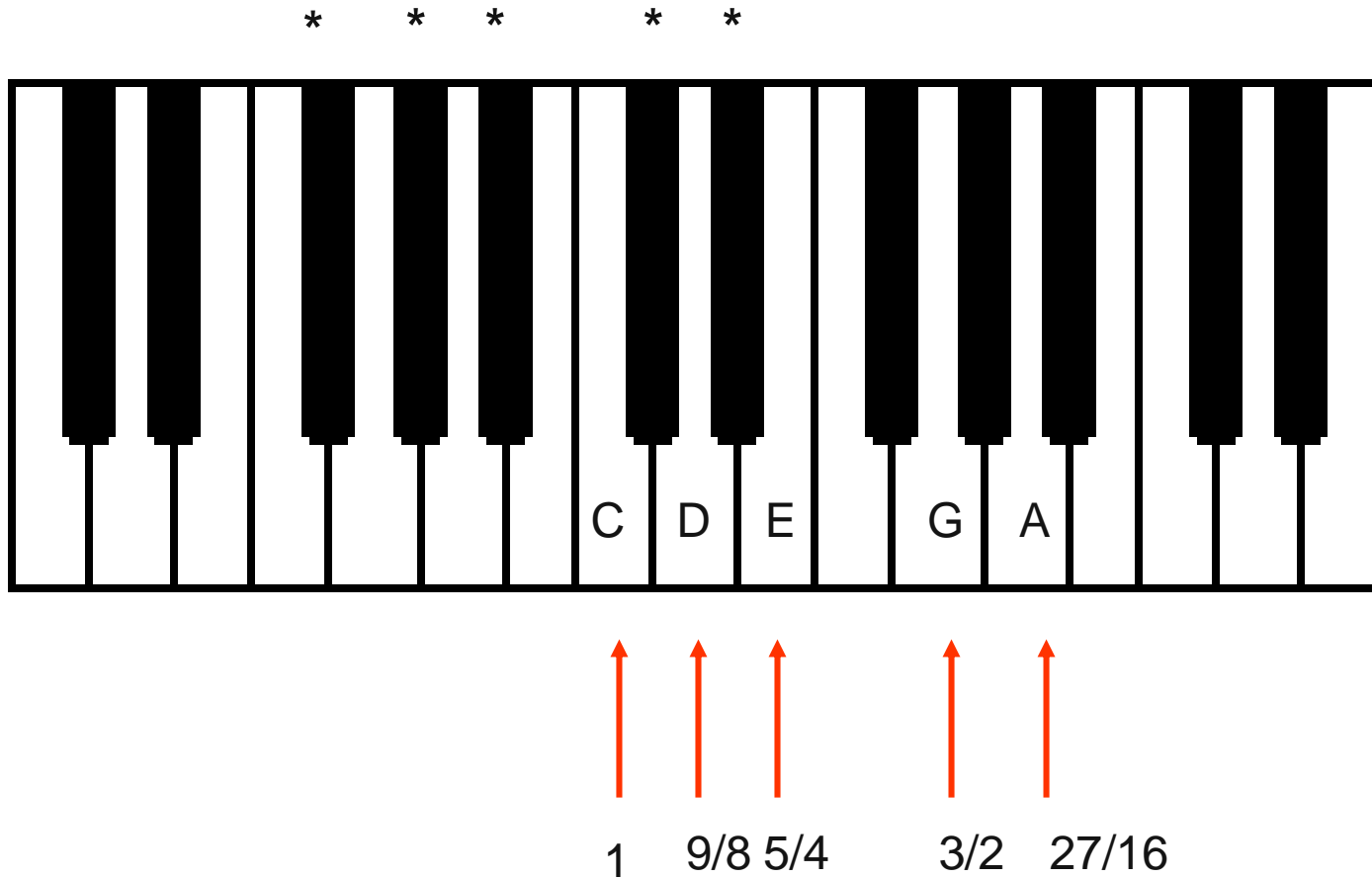
How to make a scale using notes with overlapping harmonics



Musical interval – two notes sounded simultaneously
can sound good together (CONSONANT)
Intervals are the foundations of musical harmony

*If the **ratio** of the frequencies is a small integer fraction => harmonics overlap
and the interval sounds good....pick notes on your scale for CONSONANCE*

A simple scale - the pentatonic

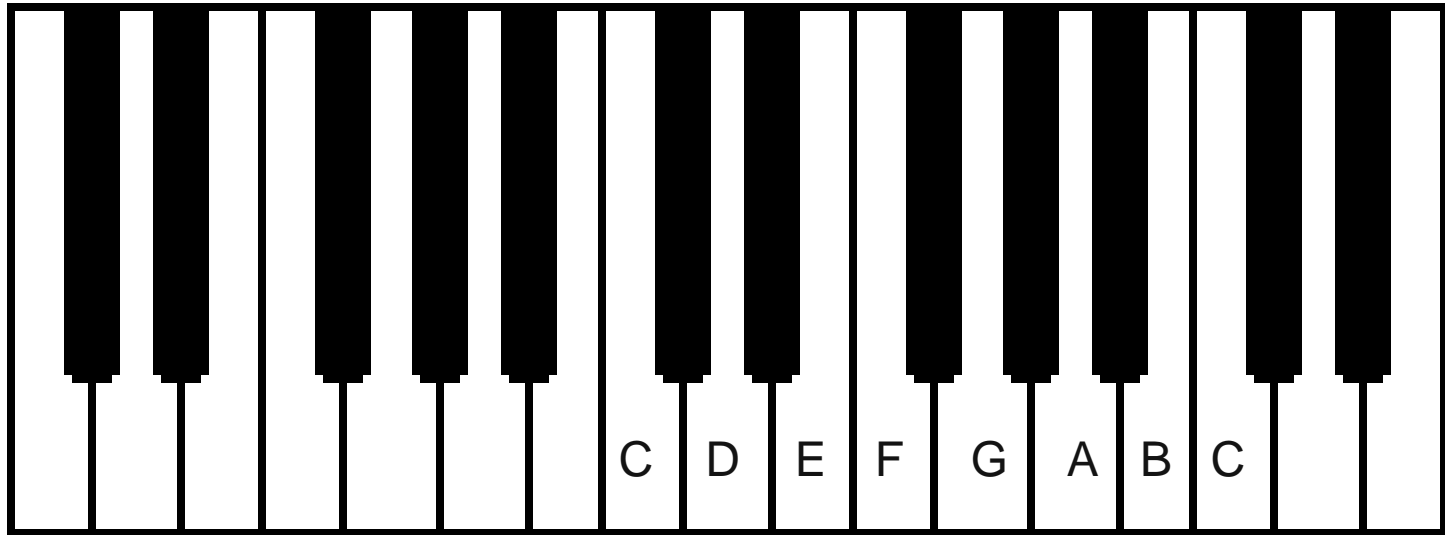


Common to many civilizations and used in jazz

Natural (Just) Scale Pitch Ratios

Note	Pitch Ratio to C	Frequency of Upper Note based on C (Hz)
C	1	261.63
C#	$25/24$	272.54
D	$9/8$	294.33
D#	$6/5$	313.96
E	$5/4$	327.04
F	$4/3$	348.83
F#	$45/32$	367.93
G	$3/2$	392.45
G#	$8/5$	418.61
A	$5/3$	436.06
A#	$9/5$	470.93
B	$15/8$	490.56
C'	2.0000	523.26

Diatonic Scale



“Tonic” is C here

Doh, Re, Mi, Fa, So, La, Ti, Doh....

Simple harmony – three note chords: the triads in the key of C



C E G M3 P5 C Major Triad



D F A m3 P5 D Minor Triad



E G B m3 P5 E Minor Triad



F A C M3 P5 F Major Triad



G B D M3 P5 G Major Triad



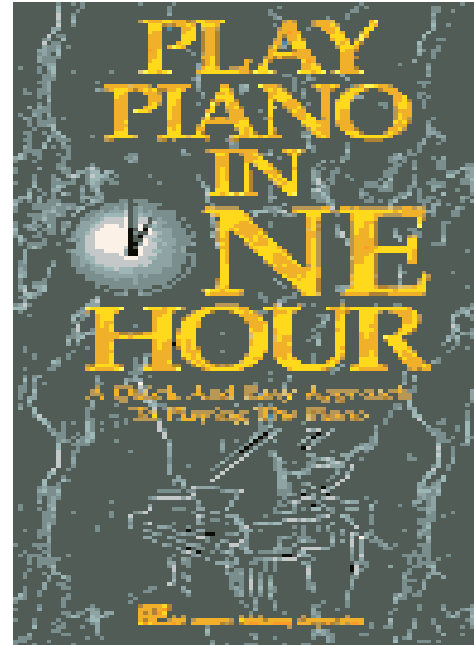
A C E m3 P5 A Minor Triad



B D F m3 d5 B Diminished Triad

Three chords and you're a hit!

- A lot of folk music, blues etc. relies on chords C, F and G



CANON IN D

JOHANN PACHELBEL

Arranged for Piano by Robert Schultz

Moderato grazioso

(poco staccato)
mp

pedal simile

p espressivo
pp

Based only on diatonic chords in one key (D in this case)

Equal temperament scale

Note	Frequency (Hz)	Difference from Just Scale (Hz)
C	261.63	0
C#	277.18	4.64
D	293.66	-0.67
D#	311.13	-2.83
E	329.63	2.59
F	349.23	0.4
F#	369.99	2.06
G	392.00	-0.45
G#	415.30	-3.31
A	440.00	3.94
A#	466.16	-4.77
B	493.88	3.32
C'	523.25	0

Step
(semitone) =
 $2^{1/12}$

*Pianoforte
needs
multiple
strings to hide
beats!*

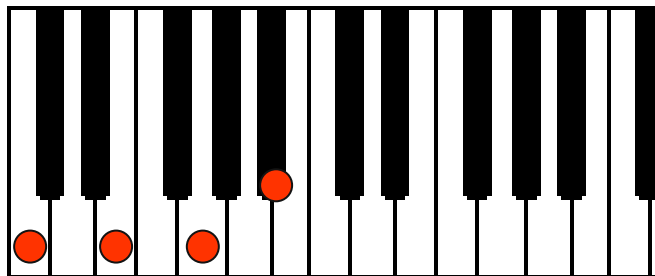
Mostly Mozart

The image displays a musical score for a piano sonata in A major, specifically measures 63 through 72. The score is written for a grand piano, with a treble and bass staff joined by a brace. The key signature is one sharp (F#), and the time signature is 4/4. Measures 63-66 show a melodic line in the treble staff with eighth and sixteenth notes, and a supporting bass line. A repeat sign is present after measure 64. Measures 67-71 feature a more active bass line with eighth-note patterns, while the treble staff has chords and occasional melodic fragments. Measure 72 begins with a piano (*p*) dynamic and features a melodic line in the treble staff with slurs and fingerings. The score includes various musical notations such as slurs, ties, and fingerings (e.g., 1, 2, 3, 4, 5).

From his Sonata in A Major

The “Dominant 7th”

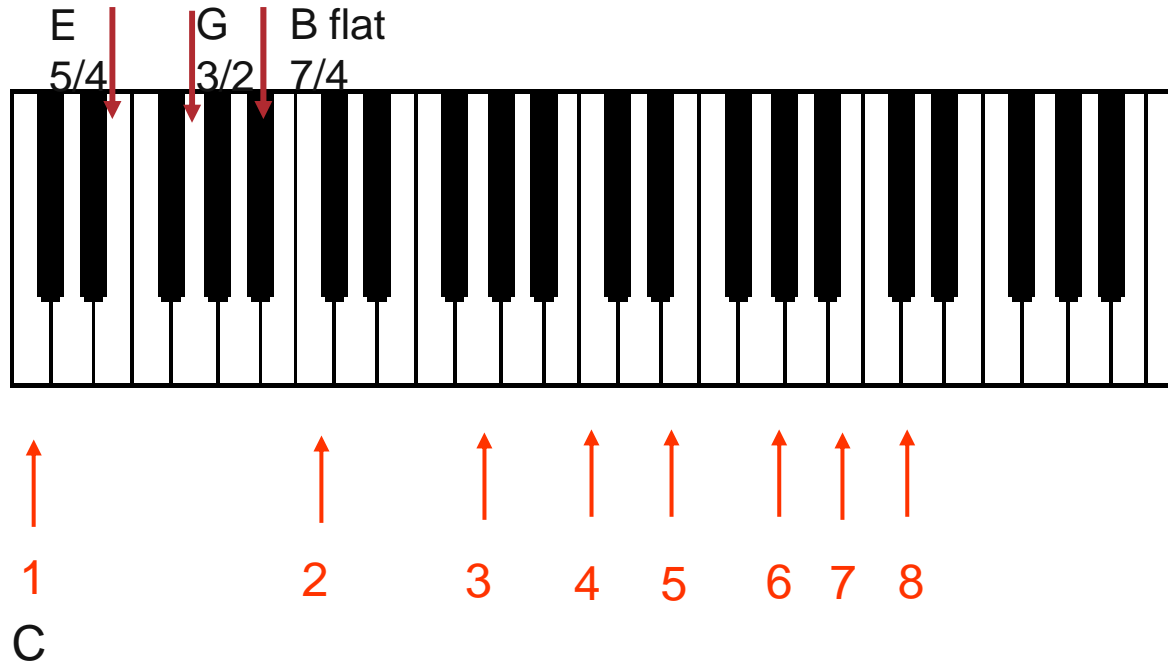
- The major triad PLUS the minor 7th interval
- E.g. B flat added to C-E-G (in the key of F)
- B flat is very close to the harmonic 7/4
 - Exact frequency 457.85 Hz,
 - B flat is 466.16 Hz
 - B is 493.88 Hz
 - Desperately wants to resolve to the tonic (F)



*B flat is not
in the diatonic scale for C,
but it is for F*

Also heading for the “blues”

How to make a scale using notes with overlapping harmonics

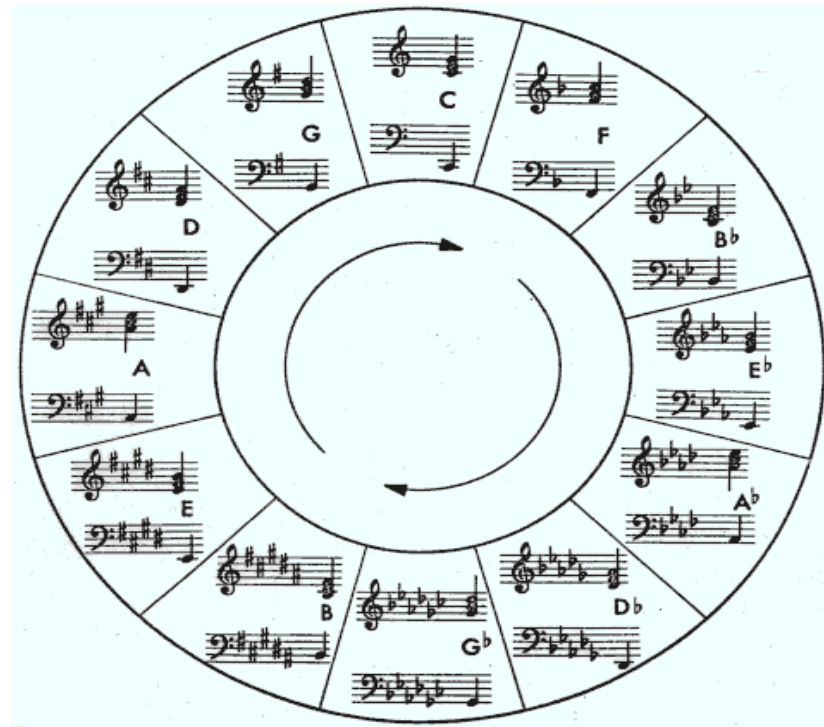


Concept of intervals – two notes sounded simultaneously which sound good together, foundations of musical harmony

Ratios of frequencies are integers \Rightarrow harmonics overlap....

Circle of Fifths

- Allows modulation and harmonic richness
 - based on dominant 7th
 - needs equal temperament
 - allows harmonic richness



BOSSA NOVA

THE GIRL
FROM IPANEMA

MUSIC BY ANTONIO CARLOS JOBIM
ORIGINAL WORDS BY VINICIUS DE MORAES
ENGLISH WORDS BY NORMAN GIMBEL

129

A F#m7 G13

Tall and tan and young and love - ly the girl from I - pa - ne -

ma goes walk - ing, and when she pass - es, each one she pass - es goes "aah!"

When she walks she's like a sam - ba that swings so cool and sways so gen - tle that when

she pass - es, each one she pass - es goes "aah!" Oh,

but I watch her so sad - ly. How can I tell her I

love her? Yes, I would give my heart glad - ly, but each

day when she walks to the sea, she looks straight a-head not at me. Tall and tan and young

and love - ly, the girl from I - pa - ne - ma goes walk - ing, and when she pass - es I smile,

but she does - n't see. She just does - n't see. No, she does - n't see.

B Gbm7

C F#m7

7(b5) F#m7 Gb7(b5) Gb7(b5) F#m7 Gb7(b5) F#m7

Yesterday..

Yesterday

Words and music by
John Lennon and Paul McCartney.
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12 Brunson Street, London W1X 7AH.



Moderato

Yes-ter-day,

p e dolce

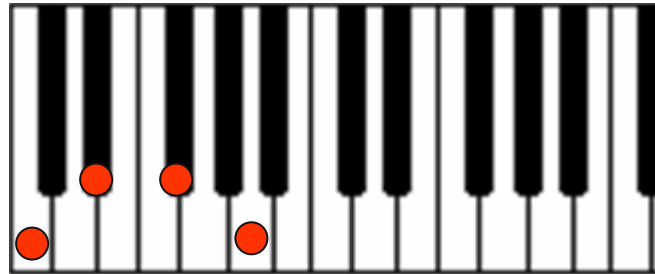
all my trou-bles seemed so far a-way Now it looks as though they're

here to stay— Oh I be-lieve— in yes-ter-day— Sud-den-ly

Chord progression: Em7, A7, Dm, Dm/C bass, Bb, C7, F, C, Dm, G, Bb, F.

Diminished Chords

- A sound which is unusual
 - All intervals the same i.e. minor 3rds, 3 semitones (just scale ratio 6/5, equal temp -1%)
 - The diminished chord has no root
 - *Ambiguous and intriguing*
- An ability of modulate into new keys not limited by circle of fifths
 - And add chromatic notes
 - The Romantic Period was lubricated by diminished chords



C diminished

Romantic music..

Edited and fingered by
Rafael Joseffy

8
a Madame Camilla Pleyel

Nocturne

F. CHOPIN. Op. 9, N° 2

Andante (♩ = 132)

2.

espress. dolce

A flat diminished (c.f. B flat dominant 7th)

cresc. *f* *p*

C diminished (F dominant 7th)

Beethoven's "Moonlight" Sonata in C# Minor

“Blue” notes

- Middle C = 261.83 Hz
- E flat = 311.13Hz
- Blue note = perfect harmony = $5/4$ middle C = 327.29 Hz – slightly flatter than E
- E = 329.63 Hz
- Can be played on wind instruments, or bent on a guitar or violin. “Crushed” on a piano
- 12 Bar Blues - C F7 C C F7 F7 C C G7 F7 C C

Equal temperament scale

Note	Frequency (Hz)	Difference from Just Scale (Hz)
C	261.63	0
C#	277.18	4.64
D	293.66	-0.67
D#	311.13	-2.83
E	329.63	2.59
F	349.23	0.4
F#	369.99	2.06
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G#	415.30	-3.31
A	440.00	3.94
A#	466.16	-4.77
B	493.88	3.32
C'	523.25	0

Step
(semitone) =
 $2^{1/12}$

*Pianoforte
needs
multiple
strings to hide
beats!*

Crushed notes and the blues

DESPERADO

Words and Music by
DON HENLEY and GLENN FREY

Slowly

mp

(with pedal)

rit.

a tempo

Not quite ready for the blues

THE CASCADES.

A RAG.

SCOTT JOPLIN.

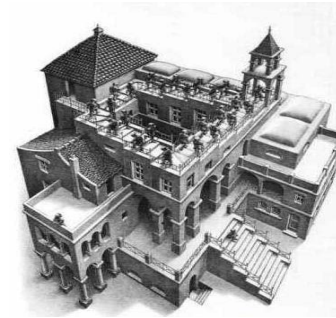
Composer of "Maple Leaf Rag."

Tempo di Marcia.

The musical score for "The Cascades" is presented in three systems. The first system is in 2/4 time, marked *mf*, and features a melody in the right hand and a bass line in the left hand. A red arrow points to the beginning of the second system, which continues the melody and bass line. The third system shows a more complex arrangement with a right-hand melody and a left-hand bass line, including a section marked *r.h.* and *l.h.* indicating a change in the right and left hands.

Ambiguities and Axioms

- Sophisticated harmonic rules (**axioms**) play on variation and ambiguity
- Once people learn them they enjoy the ambiguity and resolution
- Every now and then we need new rules to keep us excited (even though we resist!)



Music and what we do here at Argonne...

- Music and physics and mathematics have much in common
- Not just acoustics
 - Musician's palette based on physics
 - Consonance and dissonance
 - *Both involved in pleasure of music*
- Right and left brain connected?
 - Is aesthetics based on quantitative analysis?
- Music is excellent for illustrating physical principles
 - Quantum mechanics, nanotechnology, **x-ray diffraction**....

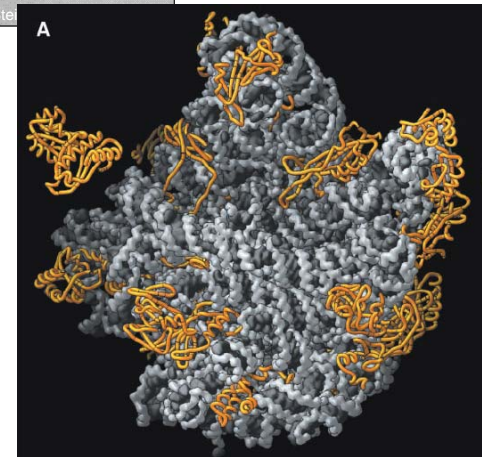
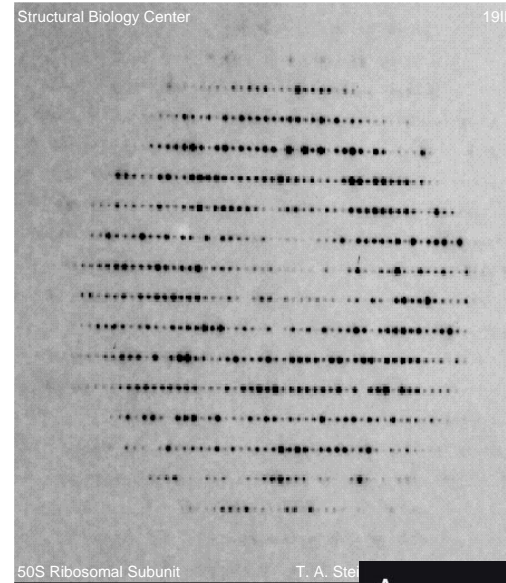
You are here...



The Advanced Photon Source (APS) at Argonne National Laboratory is the brightest source of x-rays in the Western hemisphere. Almost 3500 scientific users visit annually, experimenting in areas of science from medicine, to physics and engineering.

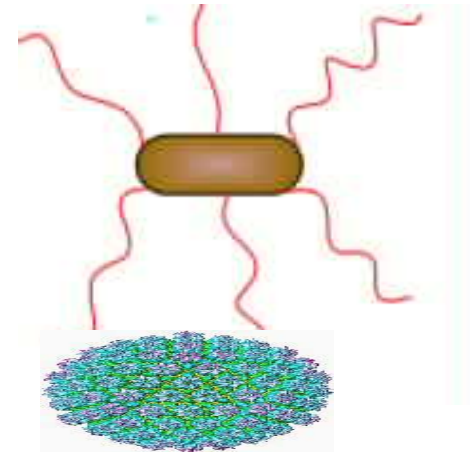
Spatial Harmonics

- Crystals are spatially periodic structures which exhibit integral harmonics
 - X-ray diffraction reveals amplitudes which gives structure inside unit cell
- Unit-cell contents?
(or instrument timbre?)



Nanotechnology

- Where chemistry, physics, materials science and biology meet
- A new way of making things from “the bottom-up” rather than the “top down”
- Also utilizes “quantum effects” in materials on a nano scale, which can be thought of as resonances in a musical context, but *electron waves* rather than *sound waves*
 - Manipulating materials on a nano scale allows you to tune these resonances



To learn more...

- “Measured Tones: The Interplay of Physics and Music”, Ian Johnston, Institute of Physics (Philadelphia) 1989, ISBN 0-85274-236-3
- **Harmony and Theory : A Comprehensive Source for All Musicians**
by Keith Wyatt and Carl Schroeder
- **A Student's Guide to Fourier Transforms : With Applications in Physics and Engineering**
by [J. F. James](#) (Author) - for math and physics students
- Many web resources, on musical acoustics, fourier analysis, physics of musical instruments....

- *This lecture will be on the web at www.aps.anl.gov*

- *Contact jmgibson@aps.anl.gov with questions*